SIMULATION BASED OPTIMIZATION OF A COLLIMATOR SYSTEM AT THE PSI PROTON ACCELERATOR FACILITIES

Y. Lee*, M. Gandel, D. Kiselev, D. Reggiani, M. Seidel, S. Teichmann
Paul Scherrer Institute, CH-5232 Villigen PSI, Switzerland

Abstract

A simulation based optimization of a collimator system at the 590 MeV PSI proton accelerator is presented, for the ongoing beam power upgrade from the current 1.2 MW [2 mA] towards 1.8 MW [3 mA]. The collimators are located downstream of the 4 cm thick graphite meson production target. These are designed to shape the optimal beam profile for low-loss beam transport to the neutron spallation source SINQ. The optimized collimators are predicted to withstand the beam intensity up to 3 mA, without sacrificing intended functionality. The collimator system is under the heavy thermal load generated by the proton beam power deposition of approximately 240 kW at 3 mA, and it needs an active water cooling system. Advanced multiphysics simulations are performed for a set of geometric and material parameters, for the thermomechanical optimization of the collimator system. In particular, a FORTRAN subroutine is integrated into CFD-ACE+, for calculating local beam stopping power in the collimator system. Selected results are then compared with those of full MCNPX simulations.

INTRODUCTION

A collimator system after the 4 cm thick graphite meson production target (Target E) has been in operation at the PSI proton accelerator since 1991. It is composed of two collimators, the collimator 2 at the beam entry side and the collimator 3 at the beam exit side. This collimator system is located 4.7 m downstream of the target E. It has an elliptic opening in order to shape the optimal beam profile for low loss beam transport to the neutron spallation source SINQ. Figure 1 shows the picture of collimator 2 before installation. It was originally designed to withstand 2 mA/1.2 MW operation of the accelerator. The deposited heat is carried away by active water cooling.

Currently, PSI is gradually upgrading the proton beam intensity from 2 mA/1.2 MW towards 3 mA/1.8 MW. In 2009, the beam intensity of 2.2 mA/1.3 MW was routinely used. In this paper, we present the simulation based optimization of the collimator system which could withstand 3 mA proton beam intensity, without sacrificing intended functionality. Only the thermomechanical aspects have been investigated. The impact of changing material properties under proton irradiation is left for future work.

* yong-joong.lee@psi.ch

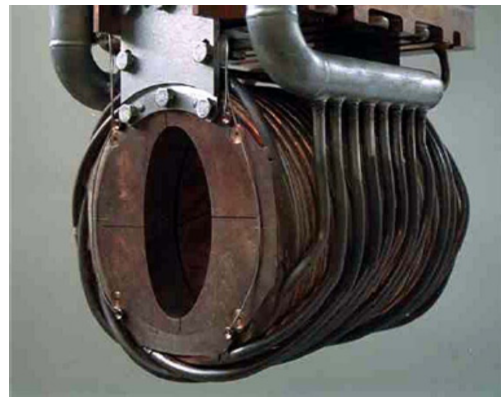

Figure 1: Collimator 2 before implementation.

PROTON ENERGY DEPOSITION IN COLLIMATOR SYSTEM

The energy loss of a proton in the collimator system is dependent on its kinetic energy and travel length. Figure 2 shows the energy loss of a 590 MeV proton per unit travel length in copper, calculated with MCNPX [1]. In order to

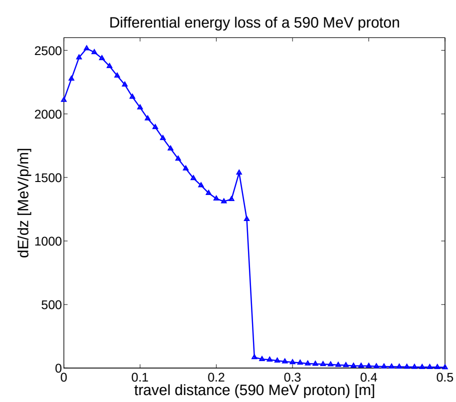

Figure 2: Differential energy loss of a 590 MeV proton in copper.

implement the energy deposition in the form of a volumetric heat source in the multiphysics simulation tool CFD-ACE+ [2], a FORTRAN 90 code has been developed. The basic inputs to the routine are the proton beam directional vector, the grid connectivity information, the differential energy loss of a proton and the proton beam current density distribution. Figure 3 shows the calculated differential energy loss configuration of a single proton in the collimator system. A design criterion is that the proton should be completely stopped within the collimator system.

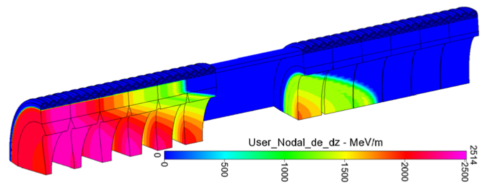

Figure 3: Differential energy loss of a 590 MeV proton in the collimator system.

The protons traveling through the collimator system have a nearly Gaussian beam profile, and the proton current density $j(x, y, z)$ is given by

$$j = \frac{I_{\text{proton}}}{2\pi\sigma_x(z)\sigma_y(z)} \exp\left(-\frac{x^2}{2\sigma_x^2(z)} - \frac{y^2}{2\sigma_y^2(z)}\right) \quad (1)$$

Here, I_{proton} is the total proton current leaving the graphite meson target for the collimator system. The standard deviations σ_x and σ_y are dominated by the scattering in the target and depend on the distance z from the graphite target,

$$\sigma_x(z) = z\sqrt{\theta_0^2 + \theta_x^2}, \quad \sigma_y(z) = z\sqrt{\theta_0^2 + \theta_y^2}. \quad (2)$$

The Coulomb scattering angle is calculated to be $\theta_0 = 5.45$ mrad. The initial dispersion angles are given by $\theta_x = 3.12$ mrad and $\theta_y = 1.26$ mrad [3]. The proton beam generates the volumetric heat source $q(x, y, z)$ which is given by

$$q(x, y, z) = \frac{j(x, y, z)}{e^+} \frac{dE_{\text{proton}}}{dz}. \quad (3)$$

The calculated proton power deposition obtained from the FORTRAN code is verified with a MCNPX calculation. Figure 4 shows the comparison of the proton power deposition in each of the six teeth in the collimator 2. The two results agree within 20 %. The difference comes from the fact that the FORTRAN routine does not take the proton scattering and secondary particle production into account.

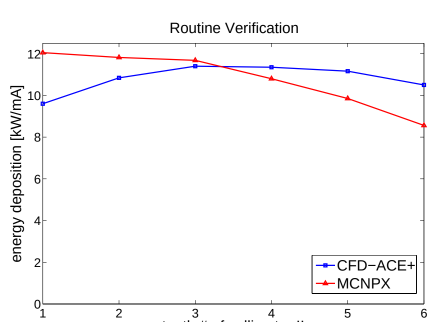

Figure 4: Comparison of power deposition predictions made by CFD-ACE+ and MCNPX.

OPTIMIZATION PARAMETERS

Material Parameter

The present collimator system is made of OFHC copper which approximately obeys the yield stress curve of the copper shown in Fig. 5. The yield stress curve of the copper

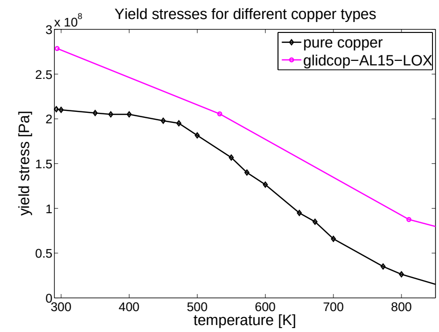

Figure 5: Yield strengths of copper [4] and glidcop [5].

shows the gradual weakening of the material strength for temperatures above 500 K. An interesting candidate material for the next generation collimator is GLIDCOP®. Glidcop is the registered trademark name of SCM Metal Products, Inc. that refers to a family of copper-based metal matrix composite alloys mixed primarily with aluminum oxide ceramic particles. The addition of small amounts of aluminum oxide has minuscule effects on the performance of the copper at room temperature, but greatly increases the copper's resistance to thermal softening and enhances high elevated temperature strength, as shown in Fig. 5.

Geometric Parameters

Each collimator in the collimator system has six diverging teeth towards the water pipe, for efficient heat conduction. The collimator opening and the diverging teeth angles are parametrized for the thermomechanical optimization study. A set of parameter studies using coupled CFD, heat and mechanical simulations has shown that the maximum temperature decreases with the widening of the collimator opening at the rate of 23 K/mm for the case of 3 mA operation of the accelerator. As the width of the teeth tip gets smaller, the maximum temperature decreases at the rate of 7.5 K/mm. These observations serve as a guideline for the geometry optimization.

THERMOMECHANICAL OPTIMIZATION

Thermomechanical Criterion

In order to estimate the mechanical strength at high temperatures, we define the yield stress index defined by

$$I_{\text{yield}}(x, y, z) = \frac{\sigma_{\text{vonMises}}(x, y, z)}{\sigma_{\text{yield}}(T(x, y, z))}, \quad (4)$$

where $\sigma_{\text{vonMises}}(x, y, z)$ is the locally calculated von Mises stress and $\sigma_{\text{yield}}(T(x, y, z))$ is the temperature dependent local yield stress shown in Fig. 5. The yield stress index serves as a failure indicator. If $\max[I_{\text{yield}}] > 1.0$, there is a considerable risk of thermomechanical failure in the collimator system.

Reference Case for 2 mA Beam Intensity

Figure 6 shows the temperature and the yield stress configurations of the current collimator system at 2 mA, obtained from a coupled CFD, thermal and stress simulation. The maximum temperature is 653 K and the maximum yield stress index is 1.08, which means that the current collimator is operating at the critical engineering limit of thermomechanical failure. For 3 mA proton beam intensity, the maximum temperature is calculated to be 834 K with the maximum yield stress index 1.69.

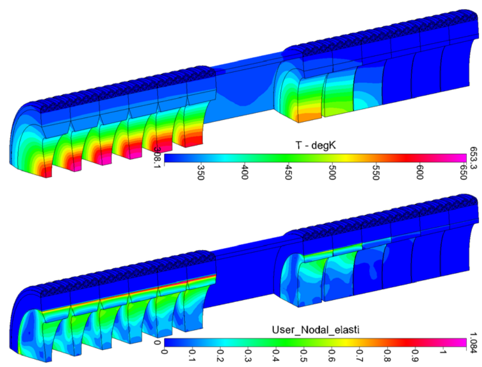

Figure 6: The temperature and the yield stress configurations of the current collimator system at 2 mA/1.2 MW.

Optimized Geometry

The beam line calculation using TURTLE [6] indicates that the collimator opening could be further widened up to 10 %. Presented in Fig. 7 are the temperature and yield stress configurations of the optimized copper collimators with 7.5 % further opening of the elliptic proton beam channel, at 3 mA. The optimized geometry shows an improved heat load balance between the two collimators. The temperature stays far below the reference temperature 653 K. The maximum yield stress index is 1.16. This is roughly equivalent to the thermomechanical load of the current collimator system at 2.2 mA which has been routinely used since 2009. So far, there has been no failure of the current collimator system at 2.2 mA.

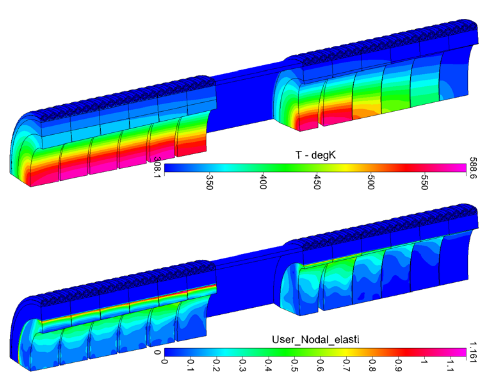

Figure 7: The temperature and yield stress configurations of the optimized collimators at 3 mA/1.8 MW.

Also tested is the material optimization. The optimized glidcop collimator shows a slightly higher maximum temperature of 604 K compared to 589 K of the optimized copper collimator, due to its lower thermal conductivity. Thanks to better mechanical properties, the glidcop collimators show a maximum yield stress index of 0.75. If one conservatively keeps the current opening of the elliptic proton channel, the maximum temperature and the maximum yield stress index are calculated to be 678 K and 0.94, for the optimized glidcop collimator system.

CONCLUSIONS AND OUTLOOK

A thermomechanically optimized collimator system for the PSI high intensity proton accelerator has been proposed. The optimized collimator system is predicted to withstand up to 3 mA proton beam intensity, if it is made of OFHC copper. With the glidcop option, about 5-25 % safety margin is expected to be gained at 3mA.

There are several issues which should be clarified before taking glidcop as the building material of the next generation collimator system. Considering the uncertainties in material data from the literature, a set of mechanical tests is planned for OFHC copper and glidcop, for different thermal conditions. The correlation between the material properties and the proton irradiation will be further investigated before the finalization of the next generation collimator system design. Also, the technical details of the brazing the water cooling steel pipe on the glidcop collimator must be clarified.

REFERENCES

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